Journal of Agrometeorology 16 (2) : 157-163 (December 2014)

Farm level water footprints of rice production based on measured and estimated crop evapo-transpiration

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ABSTRACT

Studies have been conducted to quantify water footprint (WF) on high spatial scale in which crop evapo-transpiration (ETc) was computed indirectly using empirical formula. In this study attempt has been made to quantify field level WF of rice production (varieties: 'Lalat' and 'Gayatri') in eastern India based on measured ETc. The measured values were compared with other 3 methods like Pan Evaporimeter, Bowen ratio and Penman Monteith methods. Based on measured field water balance study, 562 and 688 mm of ETc were recorded for 'Lalat' and 'Gayatri' varieties, respectively and water footprints of 2470 and 2704 m^3 t^{-1} were computed in these two respective varieties when no nitrogen was applied. But WFs of 1316 and 1394 m^3 t^{-1} were recorded under 150 kg N ha^{-1} in these two respective varieties. Thus it can be concluded that WF of a crop to a large extent was influenced by agricultural management adopted. Among different methods, the pan-evaporimeter method estimated ET_c values very close to the measured one, whereas, Bowen Ratio and Penman-Monteith methods overestimated ET_c values by 11-12 percent.

Keywords : Water footprints, Water productivity, Rice, Crop evapo-transpiration.

In eastern India, maximum area under rice (78% of total rice area in the region) is grown during wet/rainy season (July to October), of south west monsoon season. The region experiences average 1600 mm of annual rainfall and about 75% of it occurs during rainy season (June to September). This rainfall amount is sufficient to sustain normal rice growth under normal situation, but with erratic distribution of rainfall, delay in onset and occurrence of dry spells with monsoon break and also with the receipt of sub-normal rain, soil moisture deficit occurs and this led to failure of rice crop, unless supplemental irrigation is given. Changing global climatic patterns coupled with declining per capita availability of surface and ground water resources, stiff competition for scarce water resource from other sectors have made sustainable rice cultivation in the challenges.

Recognizing the importance of the facts given, quantification of water balance parameters, particularly water loss into the atmosphere (evapo-transpiration), percolation and seepage under the present management system is necessary to increase water productivity. Therefore, priority is the development of the indices that reflects fresh water resources per unit quantity of agricultural produces from a particular management system. In this regards water footprints which is the "ratio of the volume of consumptive water use to the quantity of produce obrained" can be used to indicate the requirement of direct (the green and blue water footprint) and indirect (the grey water footprint) freshwater resources (Hoekstra, 2003; Chapagain *et al.,* 2006; Hoekstra and Chapagain, 2008). The water footprint has three components viz., 'green', 'blue' and 'grey water foot prints. 'Green water footprint is the volume of water, received from rain, 'Blue water' refers to the volume of irrigated water used from surface and ground water resources, Whereas, 'grey water' or polluted water is the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards. Lower water footprint of a crop reflects its efficiency to produce more biological yield with less amount of water (Hoekstra and Chapagain, 2008).

In addition to water as a inputs, mineral nutrients, particularly nitrogen also is the key factor in achieving consistently high yield in cereals (Ponnamperuma and Deturck, 1993; Oikeh *et al.,* 2007; Worku *et al.,* 2007; Shafi *et al.,* 2011). Depending upon the socio-economic conditions of farmers of eastern India, nitrogen application to rice varied from 0 to 150 kg ha^{-1}, against the recommended optimum nitrogen rate in rainy season (Kar *et al.,* 2004). The necessitated, to make a study/ compute water footprint of rice crop under different nitrogen management practices.

Still farm level water footprints information based on measured evapo-transpiration of many crops including rice is not available, by which the estimated values can be compare with measured one. Keeping the importance of above facts in view, water footprints of rice production ('Lalat' and 'Gayatri') was computed based on measured crop evapo-transpiration in the field and compared with the values obtained from indirectly computed crop evapo-transpiration methods like pan evaporimeter, Penman-Monteith and Bowen ratio micro-meteorological methods.

MATERIALS AND METHODS

Study site

The on-farm trial was conducted at Pipli block, Puri, Odisha (Lat. $20^{O}\ 11^{/}\ 16^{//}$ Long. $85^{O}\ 83^{/}\ 53^{//}$) during rainy seasons of 2008 and 2009.

The on-farm trial was conducted in split plot design with 3 replications during rainy seasons of 2008 and 2009. The treatments were 2 varieties of rice (V_1= 'Lalat', V_2 = 'Gayatri') in main plots and five levels of nitrogen (N_0 = 0 kg N ha^{-1}, N_1 = 50 kg N ha^{-1}, N_2 = 90 kg N ha^{-1}; N_3 = 120 kg N ha^{-1}, N_4 = 150 kg N ha^{-1}) in subplots. Phosphorus and Potassium were used at the rate of 50 kg ha^{-1}. Full dose of P and K and 1/3rd of N were applied as basal in all the treatment except N_0. Only P and K were applied to N_p plot. The remaining nitrogen fertilizer was applied at tillering and panicle initiation stages in two equal splits as per the treatment studied. The 'Lalat' was a medium duration variety with the length of growing period of about 120 days while the 'Gayatri' was long duration variety with the duration of 150 days. In each year, rice was transplanted on last week of July with plant to plant and row to row distance of 0.15 m and 0.20 m, respectively. The land was prepared and puddling was done from 5th to 25th July with the rainfall received during south west monsoon period. A water layer of 40 mm was established during transplanting and maintained throughout the growing season.

Computation of water footprints

Water footprint (WFP) is expressed as the volume of water evapo-transpired or evaporated and/or polluted to grow a crop per unit mass of its economic yield, usually the unit is expressed as m^3 t^{-1} or litre kg^{-1} (Hoekstra, 2003). The WF has three components: the 'green water' footprint, WF_{green}, (evaporation of water supplied from the rain in crop production), 'blue water' footprint, WF_{blue} (evaporation of the irrigation water supplied from surface and renewable groundwater sources) and the 'grey water' footprint, WF_{grey} (volume of fresh water polluted in the production process which represents the amount of freshwater required to mix pollutants and maintain water quality according to agreed water quality standards.). Water footprints of the crop, [WF_{total} (m^3 t^{-1})] were thus calculated by dividing the total volume of 'blue', 'green' or 'grey' water use or evapo-transpired (m^3 ha^{-1}) by the quantity of the grain yield of the crop (t ha^1).

$$\mathrm{WF_{total}} = (\mathrm{WF_{green}}) + (\mathrm{WF_{blue}}) + (\mathrm{WF_{grey}}) = \frac{\mathrm{CWU_{green} + CWU_{blue} + CWU_{grey}}\ (\mathrm{m^3\,ha^{-1}})}{\text{Economic yield of the crop }(\mathrm{tha^{-1}})} \tag{1}$$

$$\text{Blue and green water foot prints} = \frac{\sum_{i=1}^{lgp} ET_{C\ green}\ (m^3\ ha^{-1})}{grain\ yield\ (t\ ha^{-1})} + \frac{\sum_{i=1}^{lgp} ET_{C\ blue}\ (m^3\ ha^{-1})}{grain\ yield\ (t\ ha^{-1})} \tag{2}$$

Reference crop evapo-transpiration (ETc) along with the percolation loss of water during crop growth period were measured in the field daily using Drum technique of Dastane (1966). Water footprint refers to a real loss to the catchment, while the percolation is actually not a loss to the catchment, therefore, percolation water was not included in water foot print calculation, only the amount of water evaporated or evapotranspired or polluted was considered to compute water footprint (Hoekstra, 2003; Chapagain *et al.,* 2006; Hoekstra and Chapagain, 2008).

Crop evapo-transpiration (ETc) was also computed using Bowen ratio method as well as using the following relationship:

$$ETc = K_c \times ET_o \tag{3}$$

Where K_c is the crop coefficient which varies with the growth stages. The K_c values at different growth stages were obtained from FAO Guideline No. 56 (Allen *et al.,* 1998) to compute crop evapo-transpiration. ET_0 is the reference evapo-transpiration depends on the climatic parameters, computed using USDA open Pan Evaporation method using the following relationship and also by Penman-Monteith (Allen *et al.,* 1998) method for comparison.

$$ET_0 = K_p \times E_p \tag{4}$$

Where, E_p is the open pan evaporation (mm day^{-1}), K_p is the pan coefficients (0.8 was taken in our study).

While calculating WF it has been assumed that any

Table 1: Total Crop evapotraspiration (ETc-T) of rice estimated by different methods.

	Water loss into the atmosphere (ETc-T)			
	PAN_E	**P_M**	**M_W_B**	**B_R**
Variety - Lalat				
Nursery	40	40	40	40
Initial stage (30 days)	148	162	137	153
Crop development stage (30days)	161	184	156	159
Mid season stage season (30days)	142	173	159	177
End season (15 days)	9	74	70.4	72
Total ET_C(mm)	**549**	**632**	**562**	**601**
Evaporation during land preparation (mm)	95	95	95	95
Total water loss into the atmosphere (mm)	644	727	657	696
Variety-Gayatri				
Nursery	40	40	40	40
Initial stage (30days)	148	152	136.5	153
Mid season (40days)	214	245	206	216
Peak growth season (40days)	188	229	211	237
End season (20days)	78	98	94.4	97
Total ET_C (mm)	**668**	**764**	**688**	**743**
Evaporation during land preparation (mm)	95	95	95	95
Total water loss into the atmosphere (mm)	763	859	783	838

E_p = Open pan evaporation (mm day^{-1}), K_p = Pan coefficients, ET_0 = Reference evapo-transpiration (mm day^{-1}), ETc = Crop evapo-transpiration (mm day^{-1}), ETC_T = Total crop evapo-transpiration (mm), M_W_B = Measured crop evapo-transpiration, PAN_E = crop evapo-transpiration computed by Open Pan Evaporimeter method, B-R = Crop evapo-transpiration computed by Bowen-Ratio method, P_M = Crop evapo-transpiration computed by Penman-Monteith method.

residual soil moisture after the crop, initial soil moisture before the land preparation, capillary rise from field and overland runoff were assumed to negligible.

The contribution of rainwater towards crop evapo-transpiration determine 'green water' footprints whereas, irrigation or 'blue water' requirement was determined by subtracting effective rainfall (ERF) from the total crop water demand. Thus, irrigation water requirement is zero when effective rainfall exceeded crop water demand. In this study USDA SCS method (the method of the United States Department of Agriculture, Soil Conservation Service) was used to compute effective rainfall.

In addition to crop water demand (includes ET_c and seepage and percolation) for rice crop, a large amount of water is needed for land preparation (WD_{LP}). Land preparation consisted of soaking, ploughing, puddling (i.e., harrowing until a soft muddy layer of 10-15 mm formed in saturated conditions) and water required to maintain the saturated conditions of the soil from the first breaking of soil to seedling/ transplanting.

The evaporation, land preparation was calculated using the following relationship.

$$E_{LP} = k \, X \, ET_0 \tag{5}$$

Where, E_{LP} is the depth of evaporation required for land soaking and preparation (mm), ET_0 is the reference evapo-transpiration during the time of soil saturation (mm), k is the evaporation coefficient equating reference evapo-transpiration to evaporation rate. The value of k of 0.9 has been taken in this study.

Table 2: Water footprints and volume of water needed under different transpiration.

Varieties	Nitrogen (kg ha^{-1})	Grain yield (kg ha^{-1})	Green and blue water footprints (m^3 ton^{-1})				Grey water footprints (m^3 t^{-1})	Total water footprint (m^3 ton^{-1})				Percolation (m^3 t^{-1})	Total volume of water needed(m^3 t^{-1})			
			M_W_B	PAN_E	B_R	P_M		M_W_B	PAN_E	B_R	P_M		M_W_B	PAN_E	B_R	P_M
I. Lalat	0	^{D}2660	2470	2421	2617	2733	0.00	2470	2421	2617	2733	2132	4602	4553	4748	4865
	50	^{C}3681	1785	1750	1891	1975	1.36	1786	1751	1892	1976	1540	3327	3291	3432	3517
	90	^{B}4605	1427	1398	1511	1579	1.95	1429	1400	1513	1581	1231	2660	2632	2745	2812
	120	^{A}4962	1324	1298	1403	1465	2.42	1326	1300	1405	1468	1143	2469	2443	2548	2610
	150	^{A}**5002**	**1313**	**1287**	**1391**	**1453**	**3.00**	**1316**	**1290**	**1394**	**1456**	**1134**	**2450**	**2424**	**2528**	**2590**
	Mean	4182						1666	1633	1764	1843	1436	3101	3069	3200	3279
II. Gayatri	0	^{D}2896	2704	2635	2894	2966	0.00	2704	2635	2894	2966	2310	5059	5148	5204	5352
	50	^{C}4005	1955	1905	2092	2145	1.25	1956	1906	2094	2146	1670	3659	3724	3764	3871
	90	^{B}5035	1555	1515	1664	1706	1.79	1557	1517	1666	1708	1329	2911	2963	2995	3080
	120	^{A}5532	1415	1379	1515	1553	2.17	1418	1381	1517	1555	1209	2650	2697	2726	2804
	150	^{A}5628	1391	1356	1489	1526	2.67	1394	1358	1492	1529	1189	2606	2652	2680	2757
	Mean	4619						1806	1760	1932	1981	1541	3377	3437	3474	3573

M_W_B = Measured crop evapo-transpiration, PAN_E = Crop evapo-transpiration computed by Open Pan Evaporimeter method, B-R = crop evapo-transpiration computed by Bowen-ratio method, P_M = crop evapo-transpiration computed by Penman-Monteith method.

The grey water footprint was calculated by dividing the pollutant load (PL, in mass/time) by the difference between the ambient water quality standard for that pollutant (the maximum acceptable concentration CON_{max}, in mass/ volume) and its natural concentration in the receiving water body (CON_{nat}, in mass/volume).

$$WF_{proc,grey} = \frac{PL}{CON_{max} - CON_{nat}} \quad (6)$$

In this study, volume of polluted water or 'grey water' footprint was estimated using nitrogen (N) only as a representative element following Chapagain *et al.* (2006). 'Grey water footprint' ($m^3 t^{-1}$) related to nitrogen pollution was calculated by multiplying the fraction of nitrogen that leaches or runoff by the nitrogen application rate (kg ha^{-1}) and dividing this by the difference between the maximum permissible concentration of nitrogen (kg m^{-3}) and the natural concentration of nitrogen in the receiving water body (kg m^{-3}) and by the actual crop yield (t ha^{-1}). In this paper, a flat rate of nitrogen leaching equal to 10% of the nitrogen application rate and used the permissible limit of '10 mg nitrate-NO_3 per litre' as per the standard recommended by EPA (2005) for nitrate content in drinking water to estimate the volume of water necessary to dilute leached nitrogen to the permissible limit. Natural concentration of nitrogen in the receiving water body was considered nil.

RESULTS AND DISCUSSION

Water loss to the atmosphere

Crop evapo-transpiration during nursery and main field and evaporation during land preparation were the real water loss that occurred to the atmosphere, thus these components were measured or estimated and used to compute water footprint (Table 1). The measured crop evapo-transpiration was compared with the values computed by other three methods like open pan evaporation, Bowen-Ratio and Penman-Monteith methods. For computing ET_c, the total growing period of the crop was divided into 4 growth stages, viz a) the initial stage: (this is the period from transplanting to the crop covered about 10% of the ground). b) The crop development stage: (this period started at the end of the initial stage and lasted; until the full ground cover 70-80%); it does not necessarily mean that the crop is at its maximum height. c) The mid-season stage: (this period starts at the end of the crop development stage and lasted until maturity; it includes flowering and grain-setting). d) The late season stage: (this period started at the end of the mid season stage and lasted until the last day of the harvest; it included ripening.

The measured crop evapo-transpiration values were 562 and 688 mm for 'Lalat' and 'Gayatri', respectively during the crop growth period. Based on the open pan evaporation (E_p) values, pan coefficients (Kp) and crop coefficients (K_c) at different growth stages of two rice varieties, the crop evapo-transpiration by pan evaporation method was determined which varied from 549 mm in 'Lalat' to 668 mm in 'Gayatri' and were close to the observed values. Among 4 methods, the highest amount ETc was estimated by Penman-Monteith method which varied from 632 mm in 'Lalat' to 764 mm in 'Gayatri' variety, which were 11-12.4 % higher than that of measured ETc values. The evaporation during land preparation was determined as 95 mm, thus total water loss into the atmosphere during cultivation process of two rice varieties were 657-783, 644-763, 727-859 and 696-838 mm under measured crop evapo-transpiration, open pan evaporation, Penman-Monteith and Bowen-Ratio methods, respectively.

Grain yield and water foot prints under different N rates

The grain yield (kg ha^{-1}) as varied with different N application rates of two rice varieties viz., 'Lalat' and 'Gayatri' was used to compute water foot print (Table 2). Both rice varieties recorded the highest grain yield with 150 kg N ha^{-1}, which were significantly different from the yield obtained with other N doses (0, 30, 60, 90 kg N ha^{-1}). With increased N levels from 0 to 120 kg N ha^{-1}, grain yields were increased significantly. Between two varieties, maximum grain yield of 5628 kg ha^{-1} was recorded in 'Gayatri' with 150 kg N ha^{-1} while the 'Lalat' variety recorded the grain yield of 5002 kg ha^{-1} under the same N treatment. Plots without application of nitrogen fertilizer produced significantly lesser grain yield (2660 and 2896 kg ha^{-1} in two respective varieties) than that of nitrogen applied plots. The results obtained in this investigation revealed that though grain yield was higher in N_4 (150 kg N ha^{-1}) but it was at par with 120 kg N ha^{-1} (N_3). This might be attributed to the fact that yield did not increase proportionally with the increase of nitrogen from 120 to 150 kg ha^{-1}.

The water footprint (WF) of rice production is sum of the water evaporated/evapo-transpired from the field/crop during its life cycle and the volume of water polluted due to applied agro-inputs. The lowest WF i.e., volume of 'green' and 'blue' water consumed per unit quantity of rice was recorded under 150 kg N ha^{-1} in both the varieties (Table 2).

On the other hand, the WF of the crop was higher when no or lower doses of N were applied which might be attributed to lesser grain yield obtained in N stress plots. The WF found reduced significantly with increased dose of N from 0 to 120 kg ha^{-1} due to significant yield enhancement for both the rice varieties. Thus, it is inferred that optimum application of N has a role to enhance the yield and also to reduce WF of rice production. This suggests that the water footprint of a crop to a large extent is influenced by agricultural management to be adopted.

Since effective rainfall was less than that of the crop water demand, total WF was contributed by both 'green' and 'blue' water (Table 2). In most of the earlier studies, WF of rice was determined on higher spatial scale where crop evapo-transpiration was computed indirectly by using empirical formulae like Penman-Monteith method. In the present study attempt was made to compute WF based on measured ET_c and the result was compared with the derived WF where ET_c was estimated indirectly by open pan evaporimeter method, Penman-Monteith formula and Bowen ratio micrometeorological methods. Lowest WFs of 1316-1394, 1290-1358, 1394-1492 and 1456-1529 m^3 ton^{-1} were obtained under field measured, open pan evaporimeter method, Penman-Monteith formula and Bowen ratio micrometeorological methods, respectively when N was applied at the rate of 150 kg ha^{-1}. Among the crop evapo-transpiration estimated methods, the Penman-Monteith methods overestimated 11 to 12% WF as compared to measured values. The pan-evaporimeter method estimated WF values were closer to the measured one. The volume of percolated water unit quantity of grain yield was also computed under different N rates and are presented in Table 2. The highest volume of percolation water was observed when no N was applied with the values being 2132 and 2310 m^3 t^{-1} in 'Lalat' and 'Gayatri', respectively. On the other hand, the lowest volume of percolation water of 1134 and 1189 m^3 t^{-1} were achieved under 150 kg N ha^{-1} in two respective varieties. Total volume of water needed per unit quantity of yield was computed by summing up the water footprints and volume of percolated water. Average over the N-doses and years, 3069 to 3279 m^3 of water was estimated to require to produce 1 ton grain yield of paddy rice in 'Lalat' variety and 3377-3573 m^3ton^{-1} (litre kg^{-1}) water was needed for 'Gayatri' variety.

For rice production total water foot print of 2020 m^3 t^{-1} and percolation volume of 1403 m^3t^{-1}, respectively were computed for India by Chapagain and Hoekstra (2011), while rice water footprint was higher in Pakistan (2874 m^3 t^{-1}). Global water foot print of rice of 1674 m^3 t^{-1} was estimated by Mekonnen and Hoekstra (2011), where 'green', 'blue' and 'grey' WFPs components were determined as 1488, 443 and 242 m^3 t^{-1}, respectively.

The water footprints of crops varied across countries and regions and this was mainly due to differences in crop yields (Mekonnen and Hoekstra, 2011). Relatively small water footprints per ton of cereal crops were calculated for Northern Europe (637 m^3 t^{-1}) and Western Europe (654 m^3 t^{-1}). On the other hand, with the exception of Southern Africa, the water footprints of cereal crops were quite large in most parts of Africa. While the average crop water requirement in Europe was only 11% lower to that observed in Africa. The average water footprint of cereal crops in Europe was about three times smaller than in Africa, which can mainly be explained by the higher average yield in Europe (3.4 t ha^{-1}) compared to that observed in Africa (1.3 t ha^{-1}). A similar observation can be made for other regions as well (Mekonnen and Hoekstra, 2011).

CONCLUSIONS

Lowest WFs of 1316-1394, 1290-1358, 1394-1492 and 1456-1529 m^3 ton^{-1} were obtained under field measured, open pan evaporimeter method, Penman-Monteith formula and Bowen ratio micrometeorological methods, respectively when N was applied at the rate of 150 $kgha^{-1}$. Among the methods to estimate crop evapo-transpiration the Penman-Monteith methods overestimated 11 to 12% WF as compared to measured values. The pan-evaporimeter method estimated WF values very closer to the measured one. Average over the N-doses and years, 3069 to 3279 m^3 of water was estimated to require to produce 1 ton grain yield of paddy rice in 'Lalat' variety and 3377-3573 m^3ton^{-1} (litre kg^{-1}) water was needed for 'Gayatri' variety.

Better rainwater management and efficient application methods will reduce the blue water foot print. Higher percolation need in the first phase of the land preparation can be reduced by water saving seeding/planting methods of rice like direct dry seeding, System of Rice Intensification (SRI).

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Received : March 2014 ; Accepted : June 2014